Open Issues in Collisional Plasmas

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Introduction

Talks on "Open Issues in X-ray plasmas" usually take one of two forms:

Disaster is looming! Few rates are known to better than 30%, less than 1% of wavelengths are measured, and so we cannot determine plasma parameters accurately even with excellent data!

OR

Incremental improvements are needed, but we have the fundamentals. Theory gives us reasonable numbers, and when needed, lab measurements will do the rest.

Instead we should consider:

What can we do with Con-X?

Issues Overview

Primary Needs

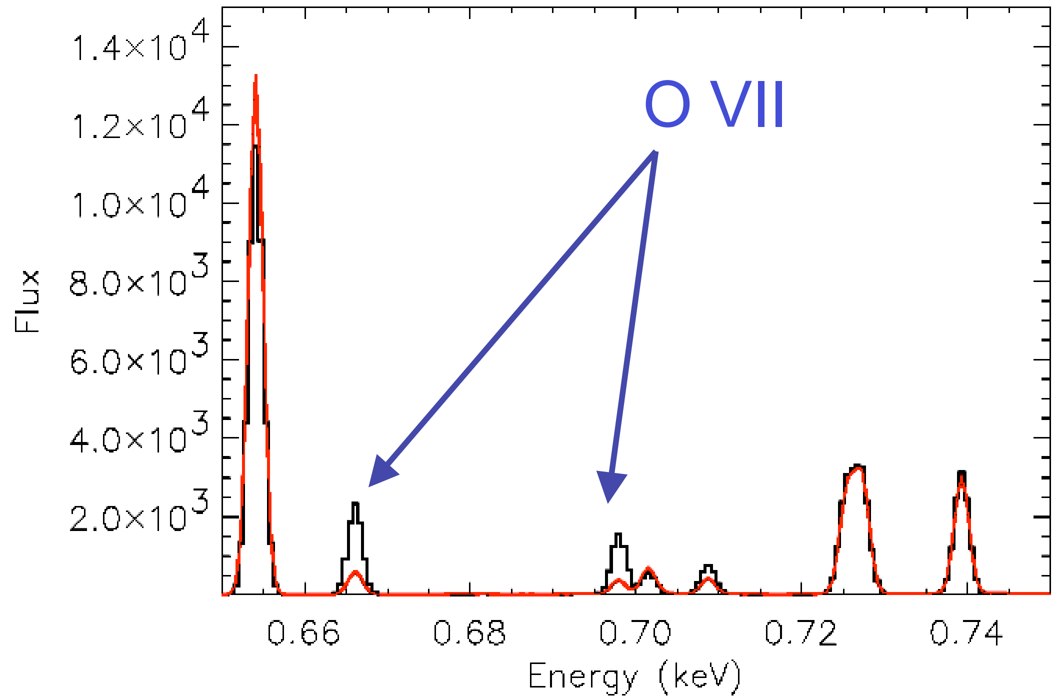
- More accurate wavelengths
- Error estimates for line strengths and ratios
- Dielectronic recombination satellite line rates, λ's
- More data on weak lines - the “pseudocontinuum”

Secondary

- Non-equilibrium plasmas: ionization balance, and rates for non-Maxwellian plasmas.
- Density-sensitive dielectronic recombination rates
- Lines beyond 40 Å

Introduction

Here is a parallel shock (pshock, kT=0.7 keV), observed with the ACIS BI:



An NEI collisional model fits the data quite well.

But with Con-X... the NEI model fails, pshock is needed.

Accurate Wavelengths

Atomic structures codes such as SUPERSTRUCTURE, HULLAC, or FAC can calculate energy levels (and therefore wavelengths) quite accurately, often to 1%.

1% accuracy at 1 keV is $\Delta E = 10$ eV

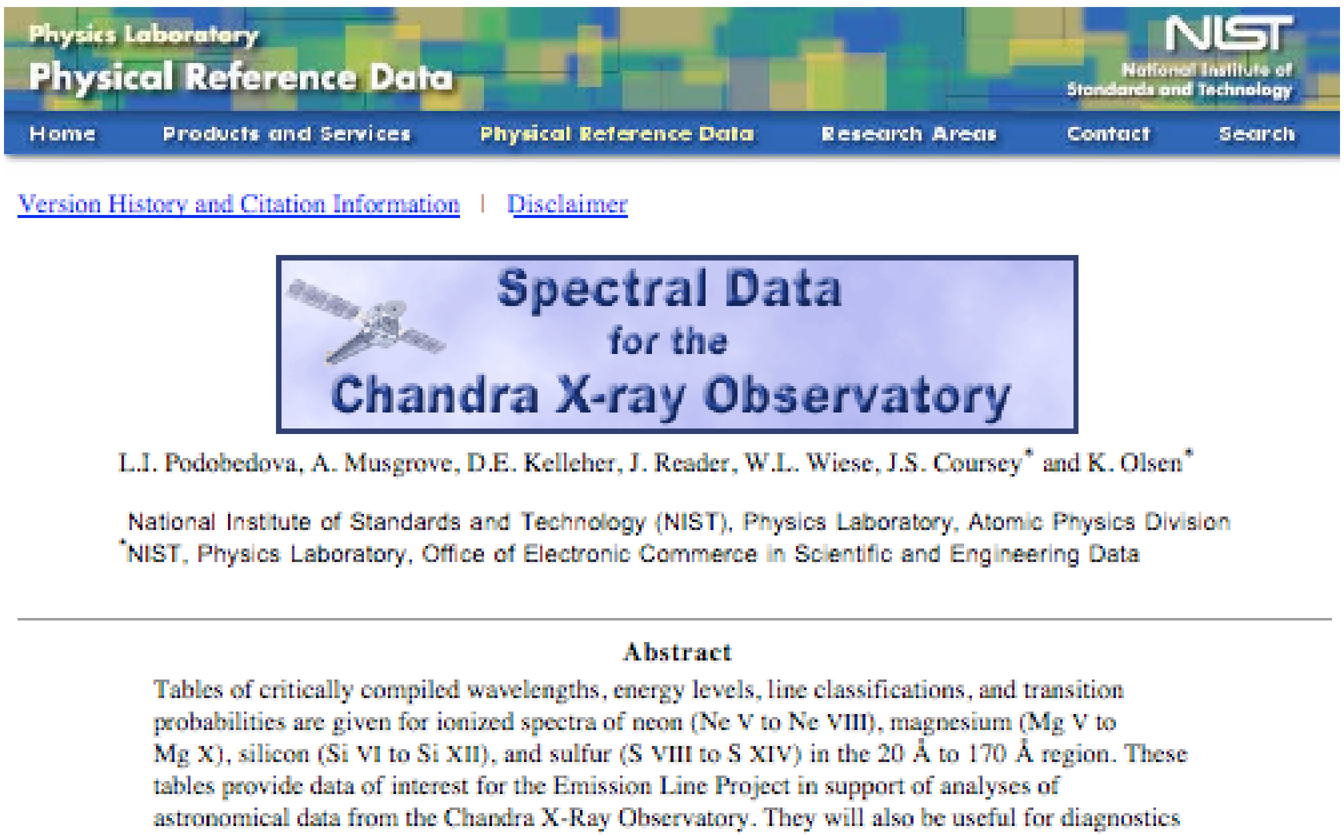
If the line is unresolvable in practice, this is acceptable if not desirable. However, for strong lines, it is totally inadequate; lab measurements are needed. But, there are fewer laboratory measurements than one might think.

Consider Fe XX. The NIST website physics.nist.gov/PhysRefData lists 64 lines for this ion shorter than 40 Å, all with ratings of D or E. The APED database contains over 2000! Even restricting the search to lines stronger than 10^{-18} ph cm^3/s finds 250 lines. EBIT measurements are providing many of these wavelengths, and many more are needed.

Accurate Wavelengths

This lack is due to many things: the difficulty of measuring forbidden lines in the lab, no perceived need for the data, and little funding for basic atomic physics. However, even a small amount of funding can produce a substantial return, as this website shows:

http://physics.nist.gov/PhysRefData/Chandra/index.html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Spectral Data for the Chandra X-ray Observatory

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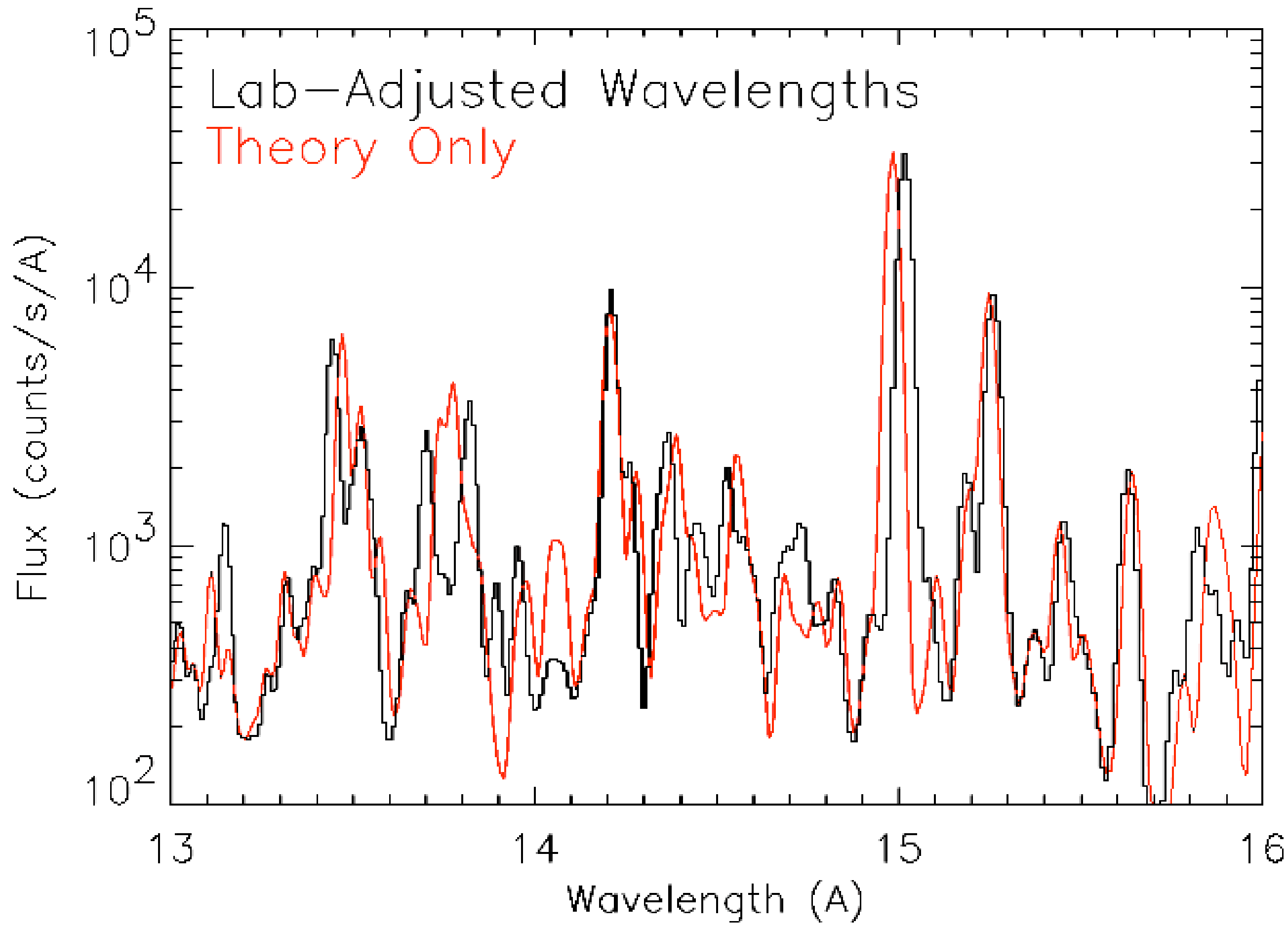
Abstract

Tables of critically compiled wavelengths, energy levels, line classifications, and transition probabilities are given for ionized spectra of neon (Ne V to Ne VIII), magnesium (Mg V to Mg X), silicon (Si VI to Si XII), and sulfur (S VIII to S XIV) in the 20 Å to 170 Å region. These tables provide data of interest for the Emission Line Project in support of analyses of astronomical data from the Chandra X-Ray Observatory. They will also be useful for diagnostics

Accurate Wavelengths

Of course, the real question is, does this even matter? Consider a Con-X observation of a 0.5 keV thermal (APEC v1.3.0) plasma:



Error Estimates

Collisional plasma models will never be perfect.

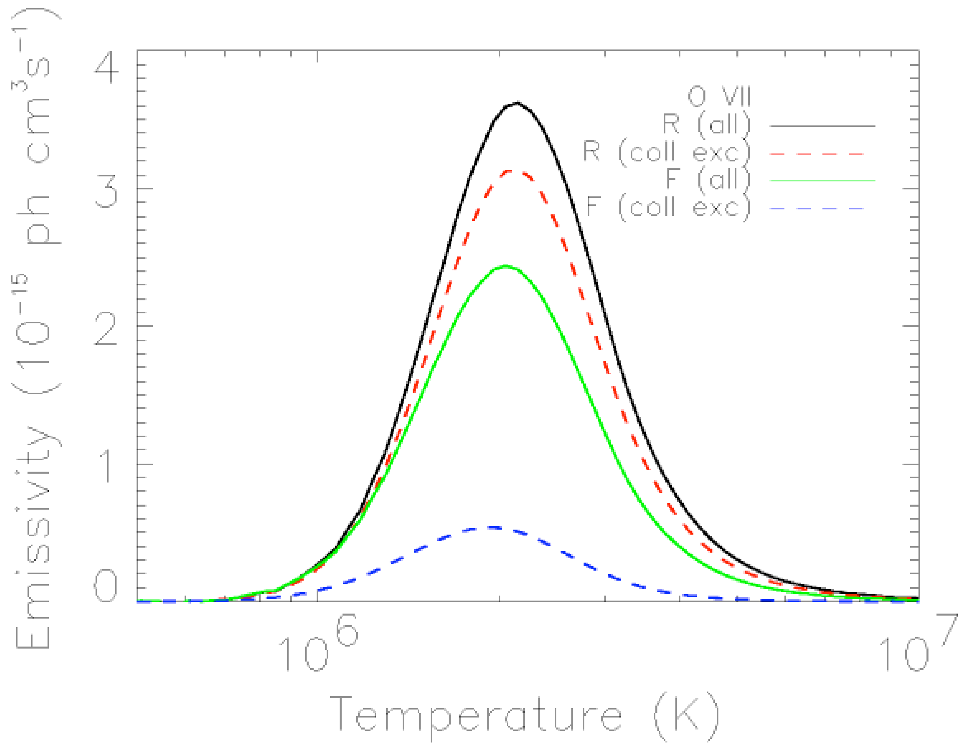
But we will need to know if a pair of O VII lines signals that the NEI model must be replaced by a pshock model, or if the discrepancy is just due to atomic physics?

Savin & Laming (2002) showed how errors in the atomic physics affected abundance measurements. XSPEC and Sherpa could include model errors. So why don't we have them?

To make an error estimate for line emissivities we need, at least:

- Errors for excitation rates
- Errors for DR, RR rates
- Errors due to cascades from missing levels
- For some lines, errors on radiative rates (A values)

This is much easier for some transitions than others. The resonance line of O VII (1s2p $^1P_1 \rightarrow 1s^2\ ^1S_0$) is dominated by collisional excitation:



But the forbidden line of O VII (1s2s $^3S_1 \rightarrow 1s^2\ ^1S_0$) is **not** dominated by collisional excitation.

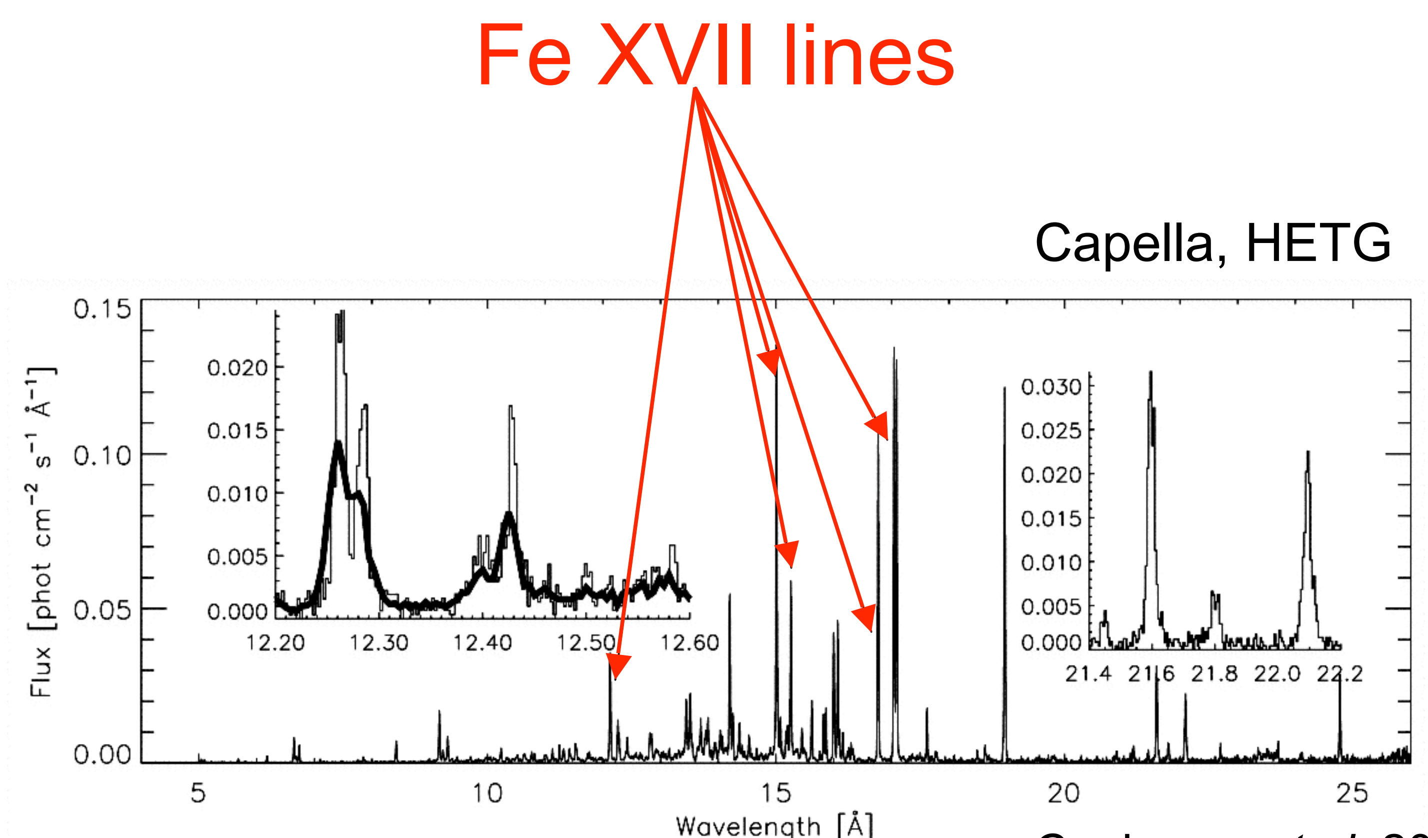
Error Estimates

Of course, even if error estimates are straightforward, they will not be uncorrelated. If the excitation rate for the O VII R line is in error, it is likely that R lines from other He-like ions, such as Ne IX, Mg XI, are also in error.

So when error estimates are made, they will not be uncorrelated or simply added in quadrature in a fitting code.

But other, more complex ions, have X-ray emission as well.

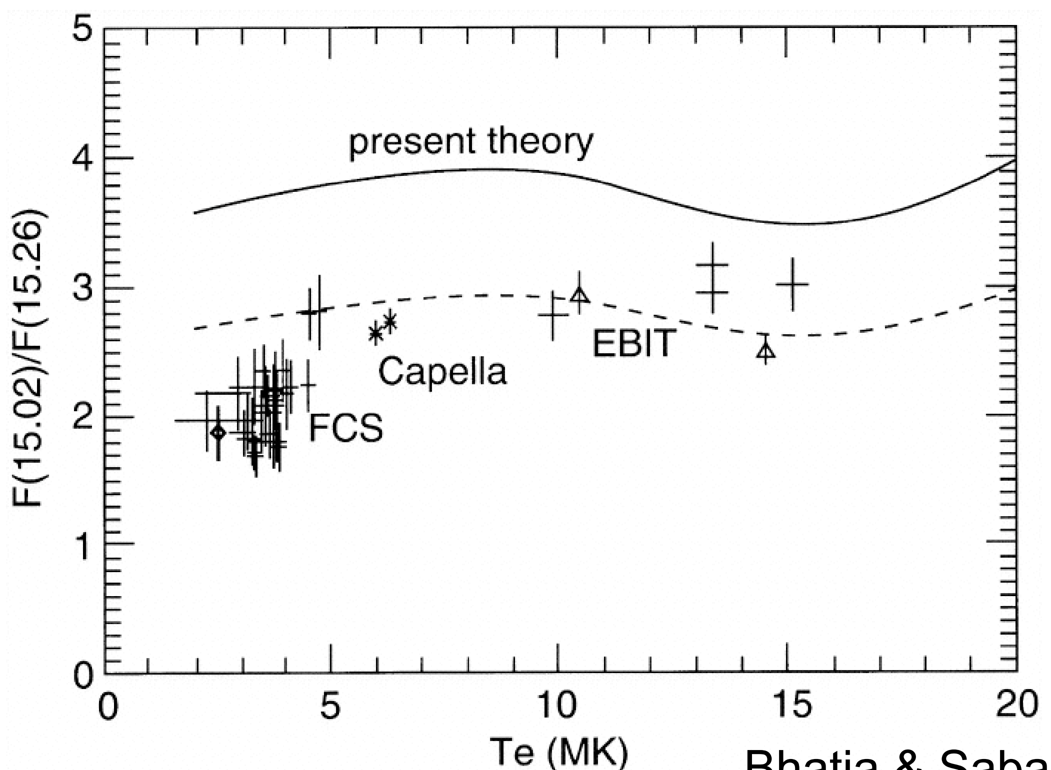
The Fe L-shell ions have many strong lines. In particular, Fe XVII has a broad temperature range (due to its relatively stable Ne-like electronic configuration), and many strong emission lines.



Canizares *et al.* 2000

Error Estimates

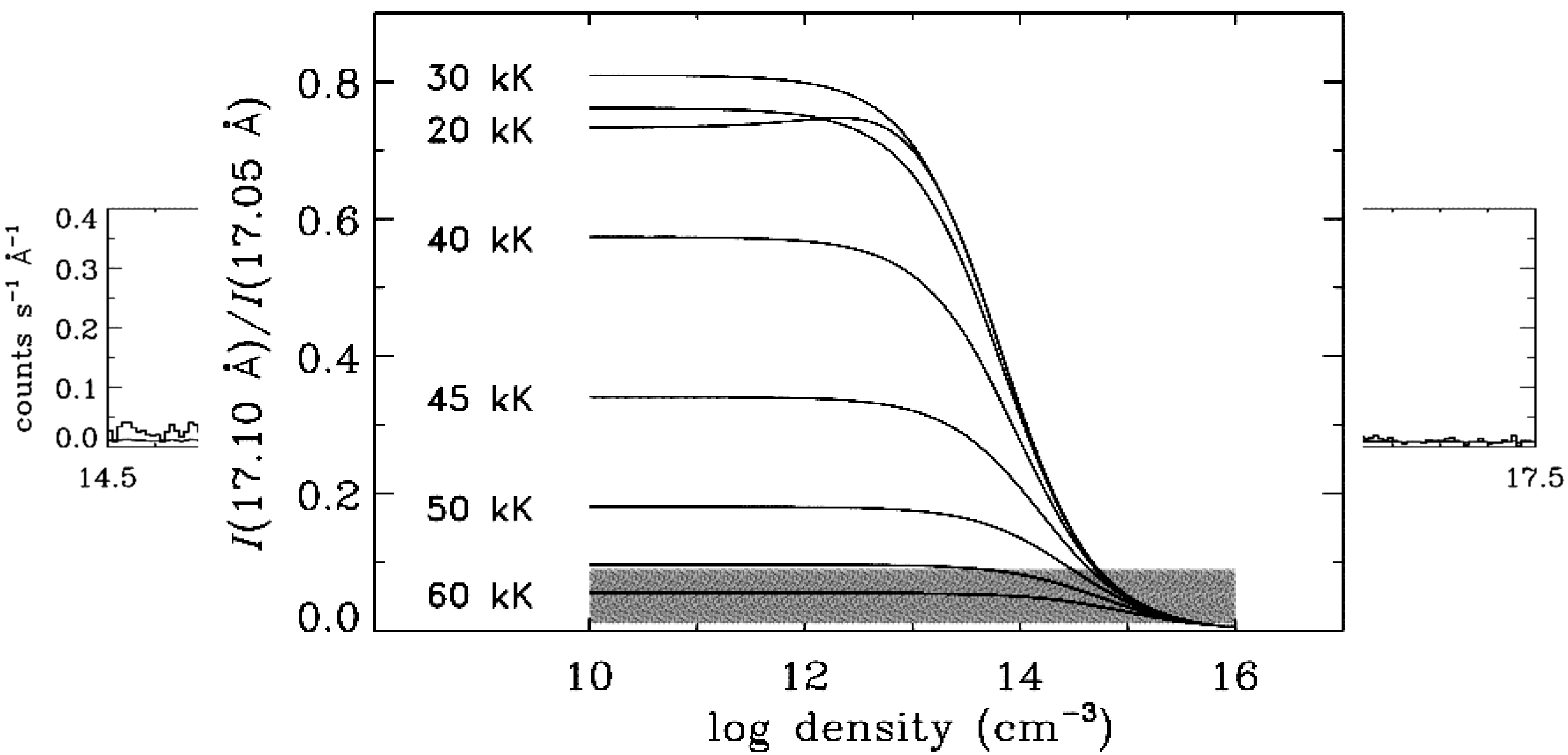
It is well-known that theory disagrees with observation and lab data for the strongest line. Suggested solutions include blending, opacity, cascades, and resonances.



Bhatia & Saba 2001

Error Estimates

This doesn't mean that Fe XVII lines cannot be used; Mauche *et al.* (2001) used them to measure the density in the accreting WD system EX Hya:

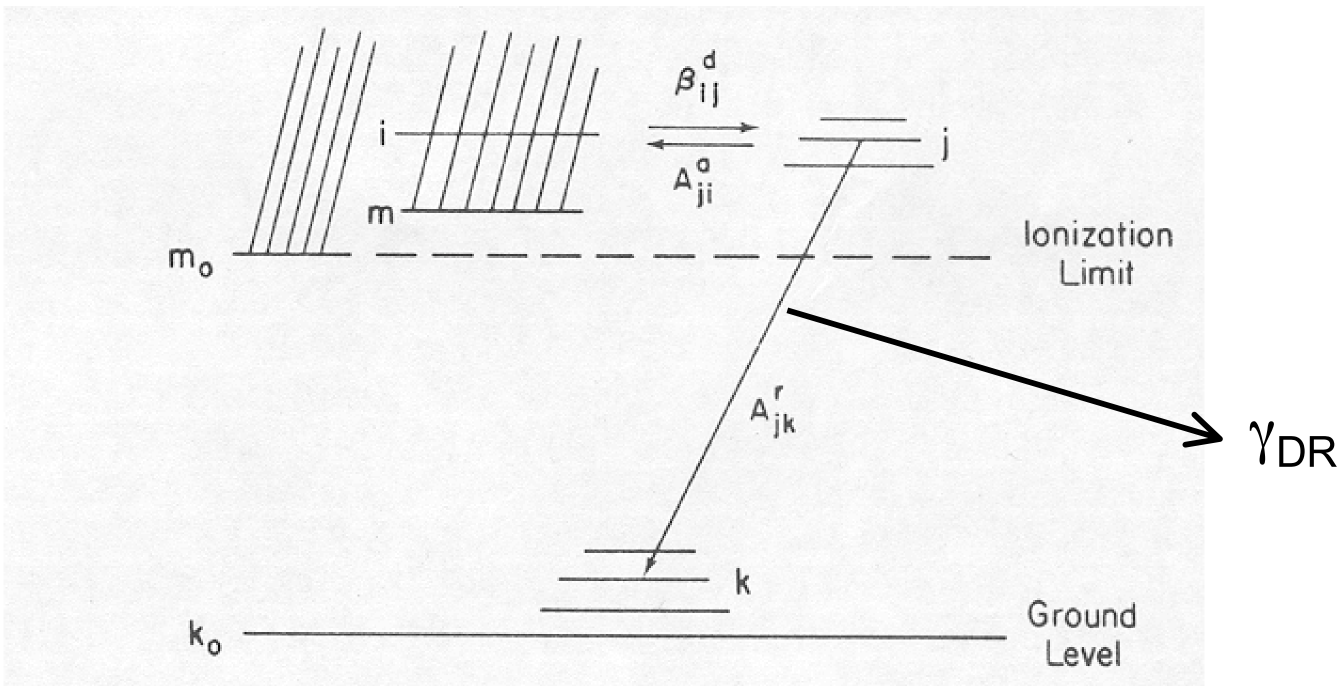


Even if the model has errors, the physics may trump them!

DR Transitions

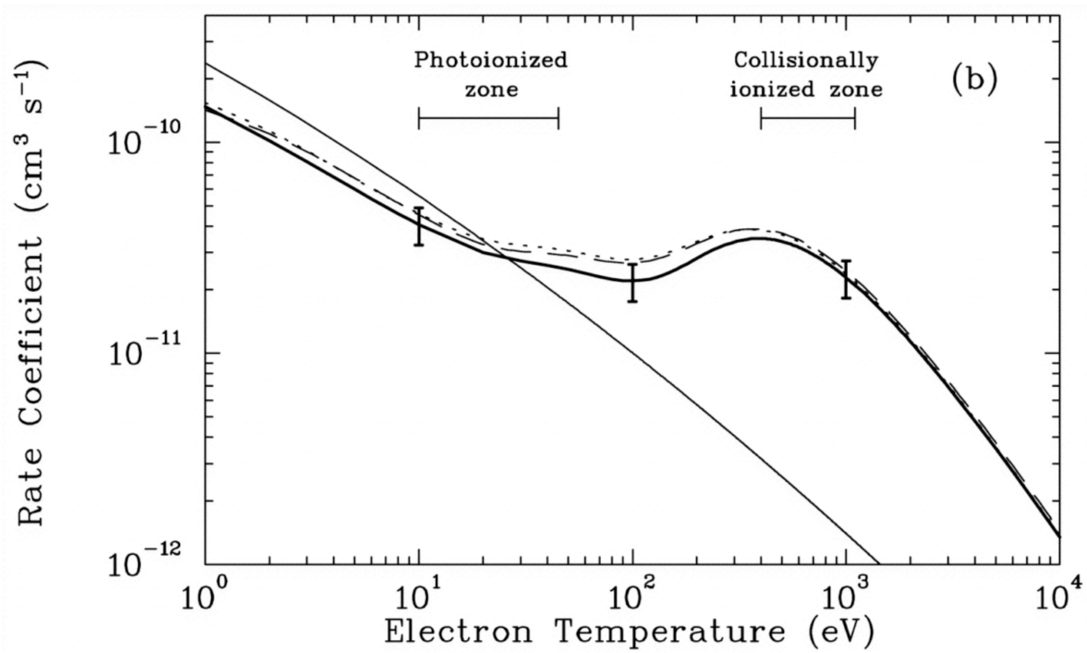
Dielectronic Recombination (DR) rates can be

- Level-separated, used to calculate DR satellite lines or summed to get ...
- Total DR, used for ionization balance calculations.



DR Transitions

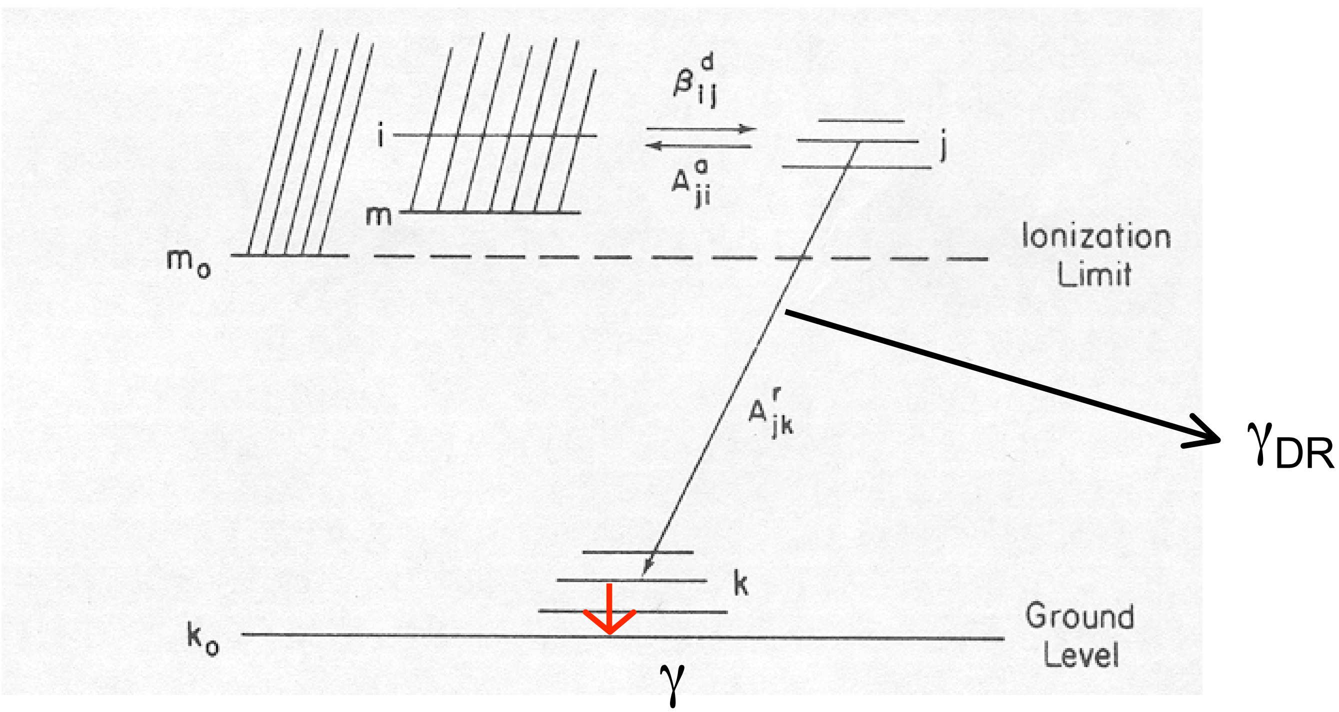
A better understanding of total DR rates will help both photoionized and collisionally ionized plasma models. Savin *et al*. (1999) showed that simply comparing various theoretical calculations is inadequate; measurements and new calculations are needed.



DR(Fe XIX→Fe XVIII): from Savin *et al*. 2002

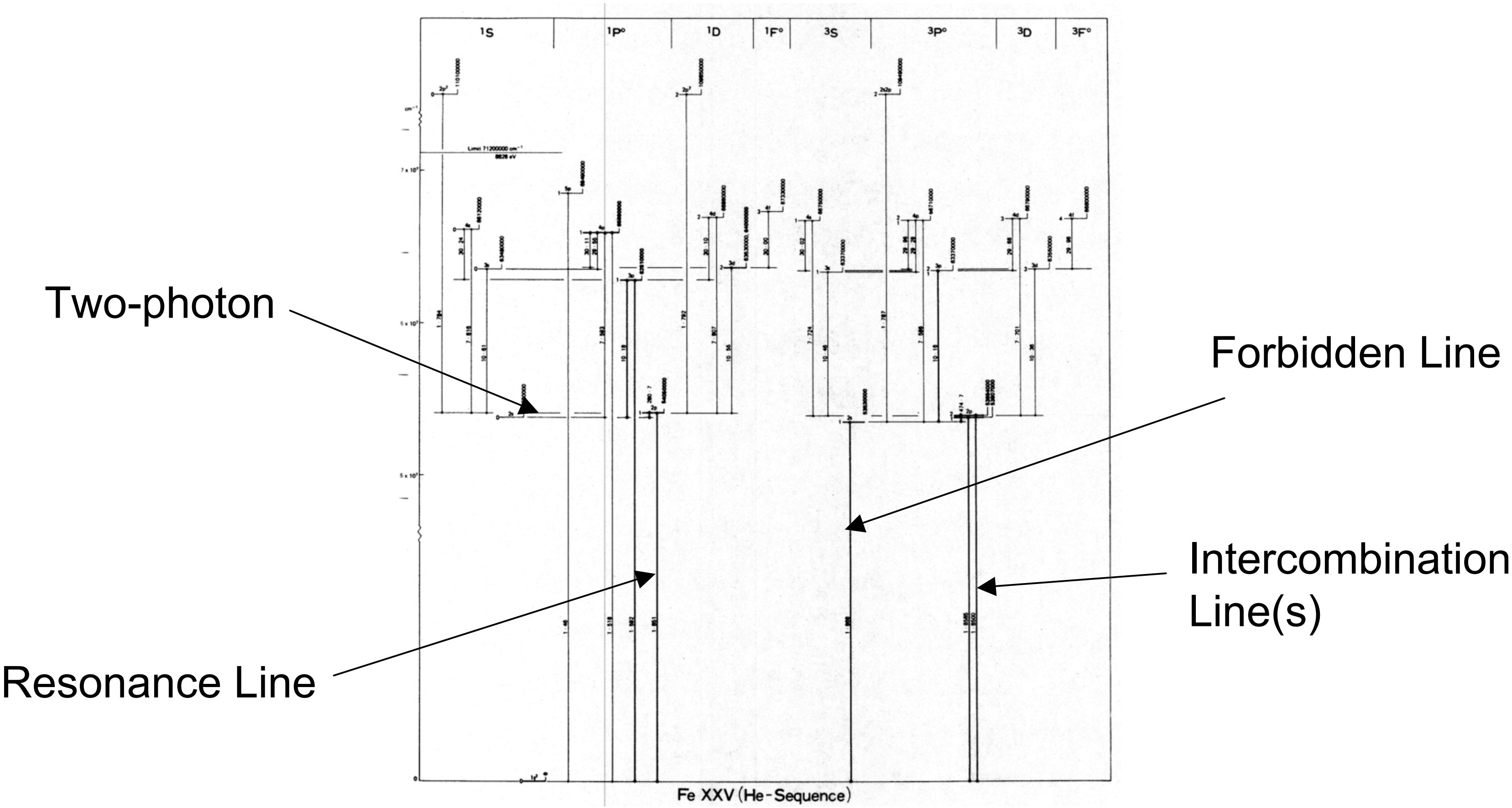
DR Transitions

However, total DR rates are only part of the story. DR leaves the ion in an excited state, which then emits a photon.



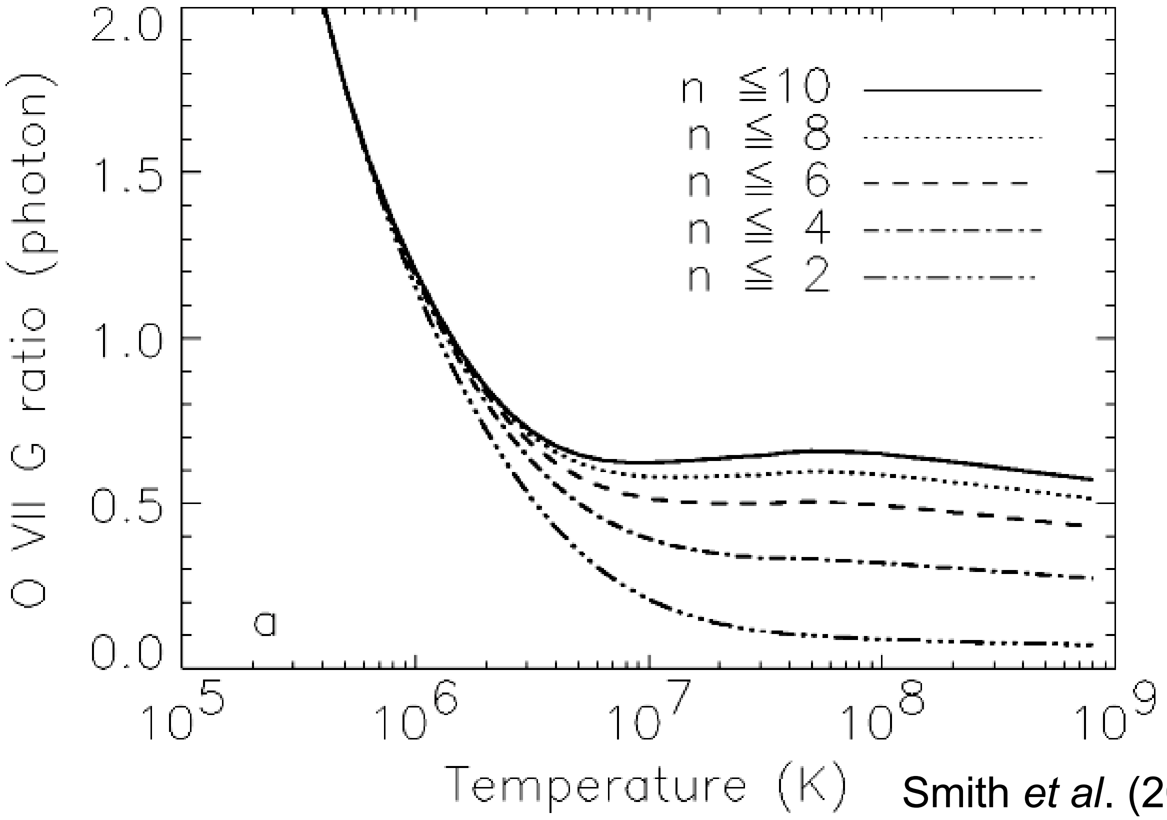
DR Transitions

In some cases, this can affect observable line ratios. Consider the ever-popular He-like triplet system, shown here for Fe XXV:



DR Transitions

As DR to more and more levels are included, the G = (F+I)/R ratio of triplet to singlet states changes, shown here for He-like O VII:



Smith *et al*. (2001)

However, little data exists for level-specific DR rates for other ions.

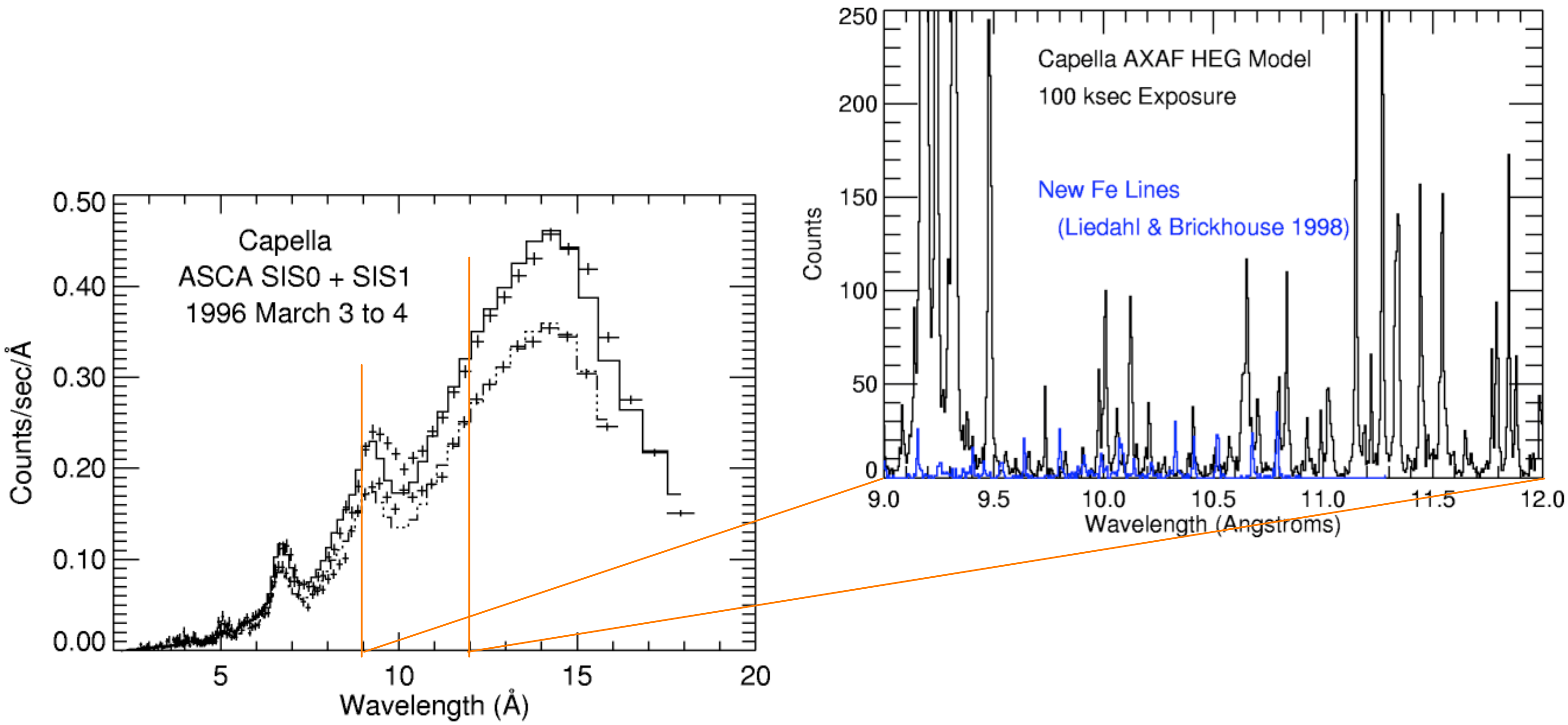
Pseudocontinuum

The "pseudocontinuum" comes from high-*n* states of L shell iron ions and other ions. Laboratory measurements of the pseudocontinuum are difficult as these lines are by definition weak and field ionization/density effects will tend to deplete high-*n* states as well.

Theoretical calculations, albeit with less accuracy than lower-*n* states, can be done. Also, since the pseudocontinuum generated by each ion will accumulate near the ionization threshold, we can identify "problem" regions of the spectrum (which will change as a function of temperature) and increase model errors there.

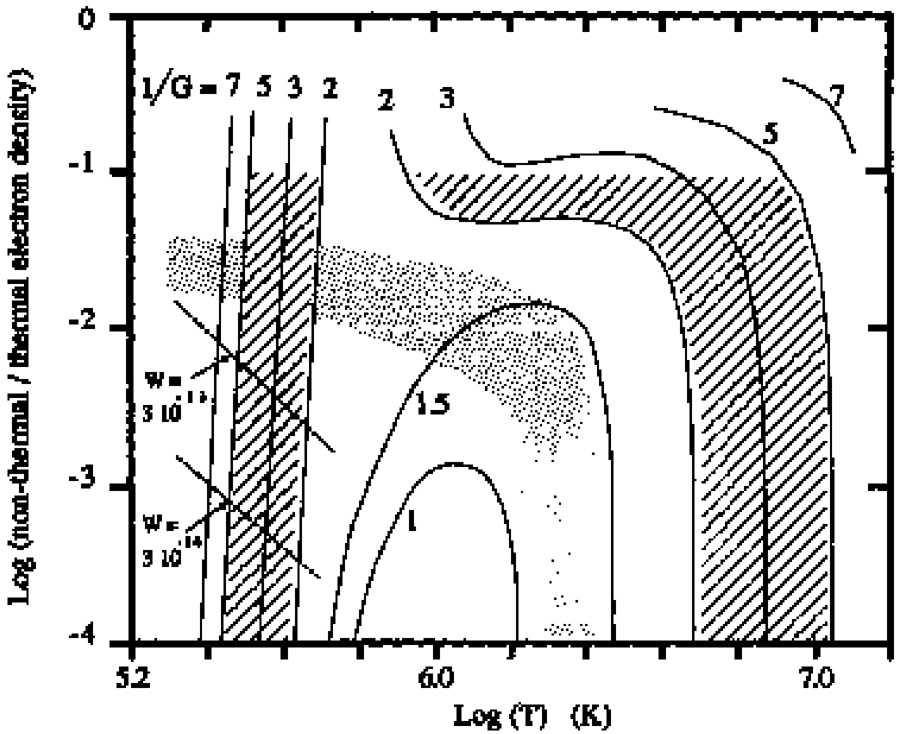
Pseudocontinuum

The pseudocontinuum is not just a recent problem; it could be seen in ASCA data as well.



Non-Maxwellian Plasmas: Secondary Issues

Relatively little work has been done on non-Maxwellian plasmas in the X-ray astrophysics community, but this has been a topic of interest for solar physicists (where the non-Maxwellian distribution can be directly measured) for some time. The problem is finding good diagnostics of, for example, a power-law tail in the electron distribution.



From Gabriel *et al*. (1991) showing the R/(I+F) ratio as a function of log(T) and the ratio of non-thermal to thermal electrons.

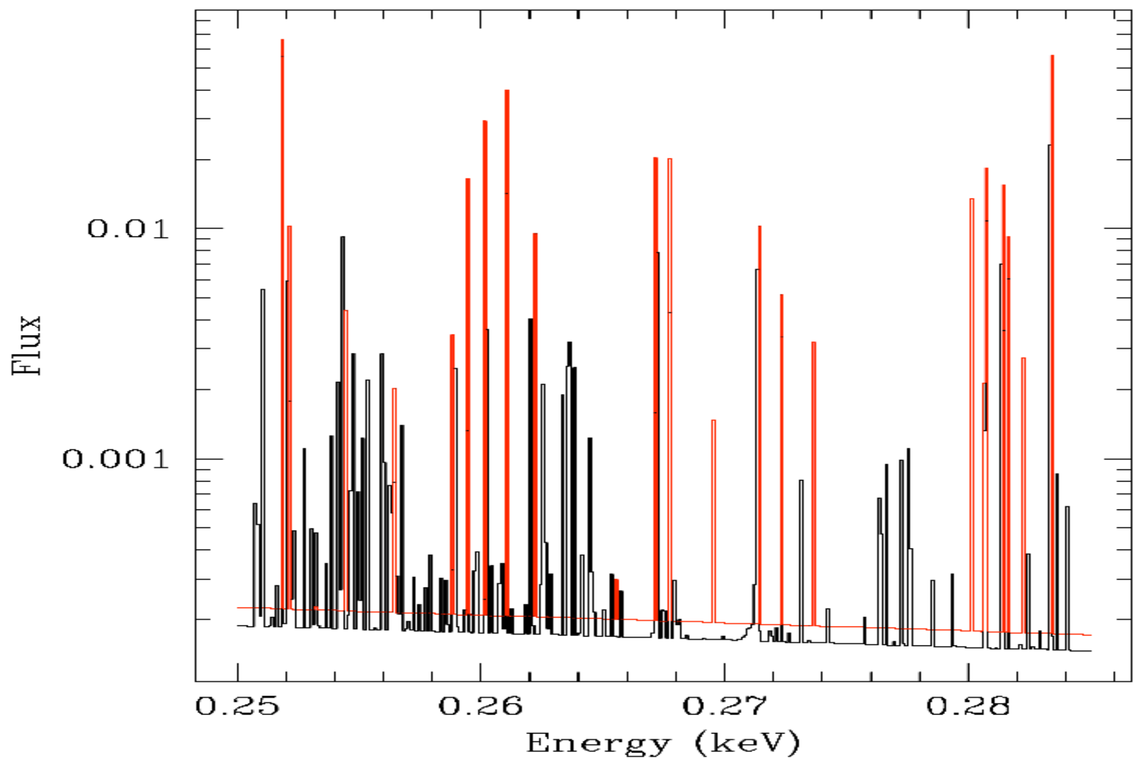
Density-sensitive DR rates

Dielectronic recombination, since it can put electrons into high-*n* states, can be density-sensitive as these electrons may be collisionally excited to other *nl* states, or ionized before recombining.

Although the density-sensitive DR satellite lines themselves may not be observable with Con-X, they will affect the ionization balance for some ions; very few ionization balance models include any density effects.

Lines between 0.25-0.284 keV

The Con-X bandpass is from 0.25-40 keV. It is worth noting that the range from 0.25-0.284 keV contains many lines of interest, if available at high-resolution:



Mekal

APEC

(kT = 0.13)

Conclusions

For Con-X (and to better understand grating observations) our primary needs are:

• Accurate wavelengths, to identify lines and blends
• Error estimates for line strengths, to know the significance of results
• DR rates/λs, to have more confidence in ionization balance calculations/line blends with DR lines
• More data on the "pseudocontinuum" of lines that will blend into measured line strengths.

We could also use:

• Ionization/recombination rates for non-equilibrium situations: ionizing/non-Maxwellian/partially photoionized plasmas.
• Density-sensitive dielectronic recombination rates
• Rates/λ's for lines in the 0.25-0.284 keV range